Active pre-alignment of the CLIC supporting system using closed-loop control as a solution for mechanical component's nonlinearities and assembly innaccuracies

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Abstract:

CERN is currently studying the feasibility of building a high energy e+ e- linear collider: the CLIC (Compact LInear Collider). One of the engineering challenges is the pre-alignment precision and accuracy requirement on the transverse positions of the linac components: 14µm over a window of 200m for the tightest tolerances. To ensure the possibility of positioning within defined requirements, a solution based on linear actuators controlled in closed-loop was chosen. However, the regulation quality could be compromised by support assembly parts' machining errors, nonlinear behavior of certain components, supporting plates' settling errors and local ground motions.

This paper describes the analysis and test results of the impact of mechanical components' nonlinearities and assembly inaccuracies on the regulation quality of the chosen control algorithm.

1-Introduction

To demonstrate, inter alia, the feasibility of remote active pre-alignment within tight tolerances, a system based on supporting structures (girders and cradles) connected in "snake"-type configuration and equipped with linear actuators is being tested at CERN (Figure 1). To achieve the requirements, all main parts of the CLIC mock-up were machined with high precision and measured to determine the position of the reference axis/zero of the component with respect to external alignment references [1][2]. The linear actuators were qualified with a resulting repeatability below 1 µm measured along their whole range.

Figure 1. CLIC test module mock-up

The mock-up components were equipped with high precision Wire Positioning Sensors (WPS) and inclinometers – giving feedback data to compute the position of supporting structures with respect to reference coordinate system.

2-"Snake" type girders configuration

Because several thousands of girders are needed for CLIC, the amount of components used (sensors and actuators) should be substantially decreased for costs reduction purposes. One of the solutions is to install motorization only at one side of a girder (MASTER cradle) and leave the non-motorized side (SLAVE cradle) to be driven by the adjacent girder as shown in Figure 2. This solution smooths out "naturally" the pre-alignment of adjacent girders.

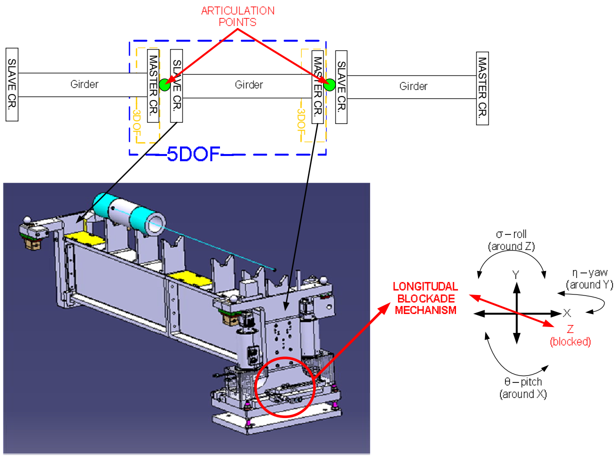

Figure 2. "Snake"-type girders configuration

Only the MASTER cradle has impact on the active pre-alignment process. Figure 3 shows its operating principle, the coordinate system and the angular motions. The cradle is suspended on two vertical actuators and is connected with one radial actuator. The actuators control the X-Y position as well as the roll of a cradle resulting in a 3 DOF mechanism. Connecting joints are elastic in direction transversal to actuator axes but rigid longitudinally, thus giving stiffness to the cradle suspension and enabling required motions. The MASTER cradle, equipped with linear actuators (considered as an object in 2D space) forms a triple, parallel P-R-R (prismatic-rotation-rotation) kinematics circuit.

Because longitudinal motion is blocked mechanically at the MASTER side, a combination of cradles MASTER-SLAVE-MASTER allows girder position control in 5 DOF (Figure 2).

The whole "snake" structure can be pre-aligned by setting the beam axis positions of all MASTER cradles in one line w.r.t. known alignment references in the tunnel coordinate system which shall be an external and independent reference for components alignment.

3-MASTER cradle kinematics versus technological constraints

The parallel P-R-R kinematics circuit of MASTER cradle can be described as 2D **-** 3 supports- Stewart Platform with Fixed Actuators (SPFA).

Standard approach to parallel mechanisms regulation is to prepare equations of the platform based on the vectors which define kinematics chain nodes. Inverse kinematics then gives the wanted actuator lengths to reach requested platform orientation. Forward kinematics of the cradle can be calculated using Newton's method.

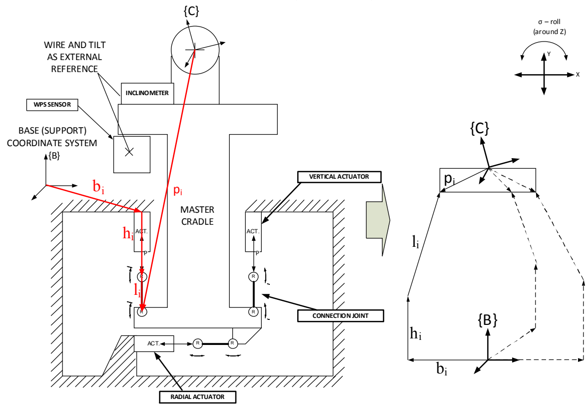

Figure 3. MASTER cradle as prismatic-rotation-rotation kinematics circuit and its vector representation

In MASTER cradle case the vertices of the platform are defined by cradle vectors ($\mathbf{p_i}^C$) and base coordinates ($\mathbf{b_i}^B$, $\mathbf{h_i}^B$, $\mathbf{l_i}^B$). The platform is supported by joints (links) of constant length $\mathbf{l_i}$, and the joints are attached to the actuators of variable height $\mathbf{h_i}$.

The approach described above (open loop control) can be correct only if we consider that all vectors are well known. It requires also calibration of all kinematic-chain components and stability of their parameters.

The biggest source of errors can be vectors $\mathbf{b_i}$ and $\mathbf{l_i}$. Vector $\mathbf{b_i}$ describes the position of the ith actuator w.r.t. {**B**} (base/reference coordinate system). However, it will be impossible to link the actuator support coordinate system "rigidly" w.r.t. tunnel coordinate system because of machining errors of actuator supports, settling errors of supporting plates and local ground motions. Vector $\mathbf{l_i}$ describes joints which are elastic transversally to the actuator axis and shall be rigid along actuator axis, but in reality the length **of** $\mathbf{l_i}$ can be changed during the displacement of the mass of the girder and of the installed components (girder centre-of-gravity displacement).

4-MASTER cradle control algorithm

To be free of suspension components constraints (section 3) – the closed control loop method was chosen for active pre-alignment [3]. The position of the common axis of the RF components mounted on the girder will be given by one WPS and one inclinometer feedback signals (both located on the MASTER cradle).

Approximate relative movements of each actuator ($\Delta \mathbf{h}_{\mathbf{i\_vertical}}$, $\Delta \mathbf{h}_{\mathbf{i\_radial}}$) to reach required girder position can be calculated using shift error vectors. These vectors are based on sensor feedback data, on requested RF components axis position and on fiducialised [2] cradles - girder geometry (Figure 5). Vector $^{\mathbf{B}}\mathbf{p_i}$ defines the current position of i^{th} cradle suspension node in {**B**} and vector $^{\mathbf{B}}\mathbf{p_i}$' presents the requested position of the same node in {**B**}. Shift error vector for each suspension node is then $^{\mathbf{B}}\mathbf{e_i} = {}^{\mathbf{B}}\mathbf{p_i}' - {}^{\mathbf{B}}\mathbf{p_i}$.

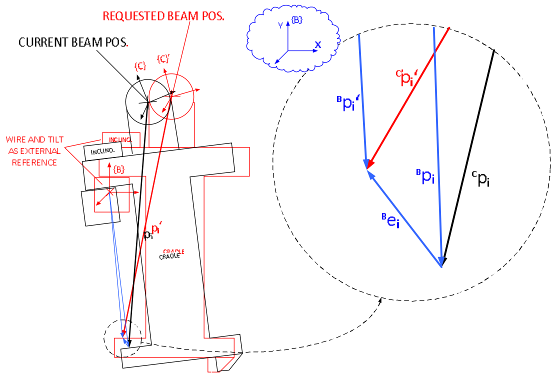

Figure 5. Shift error vector representation

The vertical actuators have a small influence in the cradle's radial position (1 mm actuator shift causes the cradle radial movement of approximately 10 µm). Likewise, the radial actuators have small influence in the cradle's vertical position. Therefore, the inverse kinematics calculations can be approximated as in equation 1.

$$e_{\mathbf{i}} = \begin{bmatrix} x_i \\ y_i \end{bmatrix}, \qquad \begin{aligned} \Delta h_{i\_vertical} &= f(e_{\mathrm{i}}) = y_i \\ \Delta h_{i\_radial} &= f(e_{\mathrm{i}}) = x_i \end{aligned} \qquad (1)$$

Because described method is based on the simplified cradle kinematics mathematical model – the pre-alignment process will need a sequence of approximations that converges to the required solution. Each new approximation is calculated on the basis of the preceding approximation (method of successive approximations).

5-Selected algorithm regulation quality

Embedding the above method in closed control loop gives iterative and convergent algorithm to pre-align a single cradle, however the target is to reach the cradle final (requested) position in the smallest number of iterations (time optimal). Also regulation trajectory shall remain inside **Current Position (CP)-Set Point Position (SP)** range and be as short as possible (to avoid RF components interconnections deformations).

According to the requirements - a series of questions linked with final regulation quality appears:

- What is the real algorithm convergence for the whole regulation area - how many iterations are needed to reach regulation Set Point?
- What could be the impact of cradle suspension components nonlinearities or machining inaccuracies for algorithm convergence?
- How looks the regulation trajectory, considering that actuators start at the same time, with the same speed after calculations? Knowing that the implemented algorithm is proportional, the regulation runs step-by-step, the supporting structure is stable after the actuators are stopped.

6-Simulations and laboratory tests results

To verify algorithm performance and questions mentioned in section 5, a mathematical model of control algorithm and MASTER cradle kinematics (Figure 6) was created.

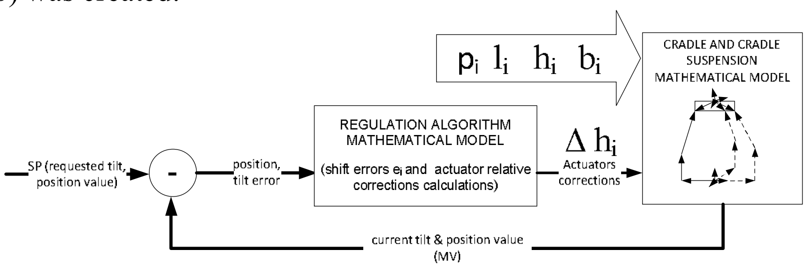

Figure 6. Shift error vector representation

To check the impact of components inaccuracies/nonlinearities and assembly errors were performed series of algorithm/cradle single step response simulations. The model have been parameterized with $\mathbf{b_i}$ vectors lengths including constant deviations (simulation of supporting plate tilt). The $\mathbf{l_i}$ vectors lengths includes constant deviations (assembly inaccuracies) and flexible joints elongation modeled in function of center of mass displacement; dependent of cradle tilt.

In parallel a series of similar single step response tests was performed on real mock-up. Random angle and position in accessible regulation space was chosen as reference “0”.

To simulate supporting plates tilt, the actuators were pre-set to keep initial tilt.

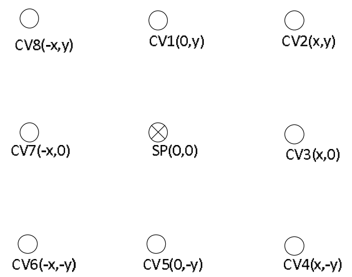

Figure 7. Map of initial tests positions (CV) around Set Point

To verify impact of assembly inaccuracy and nonlinear behavior of flexible joints – the results of alignment of two different cradles were compared. Each cradle was equipped with three different flexible joints. Precision of the joints assembly was at the level of ±0.5mm.

Position of cradle can be defined by the vector **q=[x y roll]**. The tests (simulations and mock-up) were performed for 6 series of measurements with 8 different initial regulation step positions (Figure 7). Three series were performed for big step distances **q=[±1 mm ±1 mm roll]**; roll: **0, 1, -1 mrad**. The second three series were performed for small step distances: **q=[±0.1 mm ±0.1 mm roll]**; roll: **0, 0.1, -0.1 mrad**.

Simulations with different initial regulation positions showed that the algorithm is convergent in two regulation cycles for displacements ranges: [±1 mm ±1 mm ±1 mrad] with final position error lower than 1μm. Figure 8 shows typical simulated step response. The mock-up tests verified simulations results;

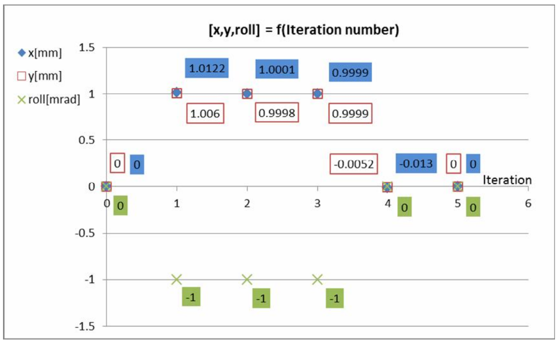

Figure 8. Simulations result for double SP change: q=[0,0,0] to q=[1,1,-1] at 1st iteration and back to q=[0,0,0] at 3rd iteration

with the WPS sensor noise at the level of 5 $\mu m_{p\text{-}p}$ and inclinometer noise at the level of 5 $\mu rad_{p\text{-}p}$ – the final position was achieved in two to maximum three regulation steps (within the sensor noise). Figure 9 shows typical response of real system.

The tests with initial displacements ranges: [±0.1 mm ±0.1 mm ±0.1 mrad] confirmed algorithm performance. Simulation shows 1 iteration convergence (precision of 1 µm). The mock-up test gives results within 1 to 2 steps.

Maximum value of position overshoot after first iteration was always below 50 µm. Figure 8 and 9 show it after 1st and 3rd iteration.

7-Conclusions

The simulations and mock-up tests results shows that successive approximation algorithm for cradle position control meets the requirement. Closed loop regulation – now only for relative displacements – freed us from problems with cradle suspension components inaccuracies. There is also no significant effect of components nonlinearities and inaccuracies for the final algorithm iteration number. Comparison of the measurement results from two different cradles shows the same, 2 to 3 step, algorithm convergence.

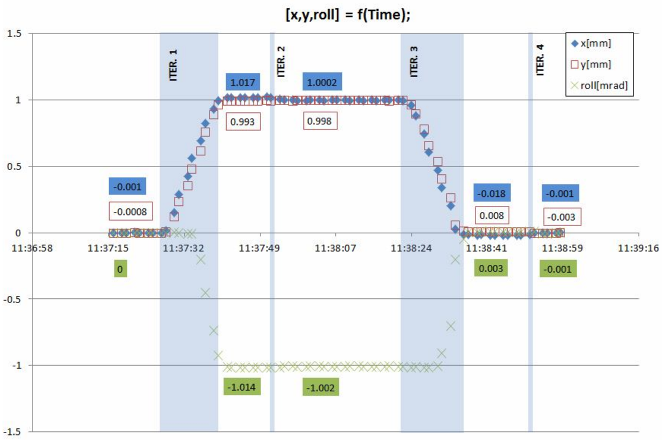

Figure 9. Experimental results for double SP change: q=[0,0,0] to q=[1,1,-1] at 1st iteration and back to q=[0,0,0] at 3rd iteration

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